CAVITATION INCEPTION WITNESSED BY SOUND PRESSURE LEVEL BOTH IN MODEL TEST AND PROTOTYPE OBSERVATION

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Abstract

The paper concerns with the relationship between cavitation inception σ_i and sound pressure level (SPL). A case study of Xiaolangdi Hydro-project has been taken as a typical example, which demonstrates the standard criterion of SPL indicating cavitation inception. Cavitation inception of an orifice plate used for energy dissipation in a tunnel spillway has been witnessed and verified both in model test and prototype observation. A design criterion has been proposed for a cavitation – free hydraulic structure. It can be served as a reference for designers as well as preliminary findings for fundamental cavitation researchers. Consequently, scale effects are discussed with an aim at suggesting an appropriate factor of safety in design.

1. Introduction

Cavitation inception is of vital importance to be accepted as a design criterion in engineering practice. However, it is more or less difficult to be detected either in model test or in prototype ob-servation. If visual inspection by naked eyes were used, it would be hardly free from being subjunctive and lack of an appropriate standard. The acoustic measurement is to be screened as a better approach. What is the relationship between the cavitation inception and sound pressure level (SPL)? The present paper intends to help clarify the reasonableness of using acoustic method. Attention will be focused on the witness of relationship between the SPL and cavitation inception, the standard of design criteria as well as scale effects in physical modeling

2. Model test findings

A case study of Xiaolangdi hydro-project has been made in a large-sized vacuum chamber, in which atmospheric pressure can be reduced according to model law, thus making possible to reproduce and simulate the cavitation phenomena as expected. The facility is shown in Photo 1.

Photo 1 General view of a large-sized vacuum chamber

A tunnel spillway of Xiaolangdi Hydro-project on the Yellow River is simulated in the model, having a scale ratio of 1: 40. The No.1 tunnel spillway has the maximum operating head of 140 m., the maximum velocity at the radial gate exit being 33-35 m/s, the maximum power of discharge for a single tunnel being exceeding. 2000 MW. Multiple-orifice plates are provided for energy dissipation, thereby enabling to reduce flow velocity with an aim at preventing or mitigating sediment abrasion due to high velocity silt-laden flow of the Yellow River. However, the orifice plate acting as an effective energy dissipater is also a genesis of cavitation. The general layout of the No. 1 tunnel spillway with orifice plate is shown in Fig.1. The highlights of model test findings are summarized as follows:

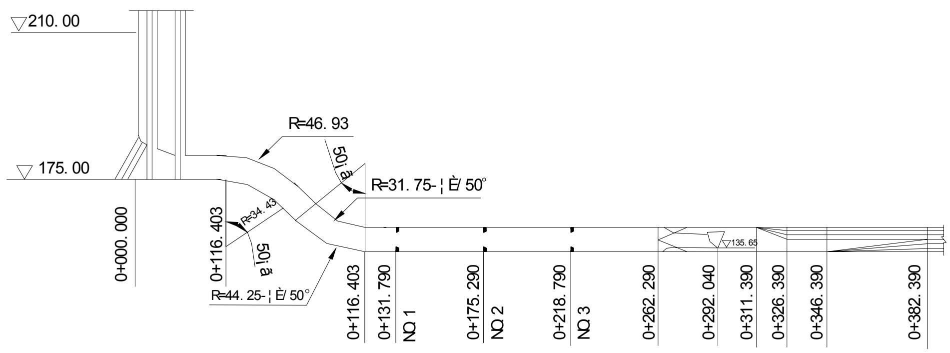

Figure 1 General layout of No.1 tunnel spillway with orifice plate

2.1 Cavitation behavior and the standard criterion distinguishing cavitation inception

As regard to the cavitation behavior and characteristics of an orifice plate, there are two main sources of cavitation, namely: one is the vortex cavitation, occurred at the upstream corner of the orifice plate. It is in the shape of an earthworm, which is immediately vanished as soon as it moves downstream; another one is the sheet cavitation, happened at the shearing layer of a jet flow downstream of the orifice plate, which sustains in a very short duration. During the stage of cavitation inception, it only appears intermittently as a flashing fragment (light refraction). As cavitation is further developed, the flashing fragment is getting larger and larger, and the time of occurrence is gradually condensed, consequently becoming uninterrupted flashing fragment, as one falls, another rises. The noise due to cavitation bubble collapse transmitted through water body to the upstream tank of the vacuum chamber can be clearly heard like the impact sound of steel wires. The cavitation sound spectrum, starting from intermittent pulse is developed to sustainable rise of sound spectrum level. In the process of model test, instruments were used to detect the energy pulse caused by cavitation bubble collapse, which was associated with visual observation. On the meantime, it was also checked by point of inflection of energy to detect that the bubble observed was really the vaporous cavitation bubble instead of gaseous cavitation bubble. The occurrence of cavitation bubble about 5 times every 2 minutes is distinguished as cavitation inception, which is recognized as the standard criterion.

2.2 Incipient cavitation number of an orifice plate and its scale effect

The scale effect of incipient cavitation number of an orifice plate is very obvious. It changes as the variation of pool level. Under the same water head, for the same shape of orifice configuration, the incipient cavitation number also increases as the model scale increases. This is the common cavitation characteristics for non-streamlined bodies. Different institutions based on their own experiments will propose different cavitation incipient number for the same orifice plate. The main cause lies on the fact that scale effect plays an important role. Usually, the Reynolds Number Re is taken as a main parameter $Re = V_d \cdot d / \upsilon$, which denotes the integrated influence of dimension, flow velocity and kinematics viscosity. Figure 2 shows the relationship between the incipient cavitation number and the Reynolds Number for an

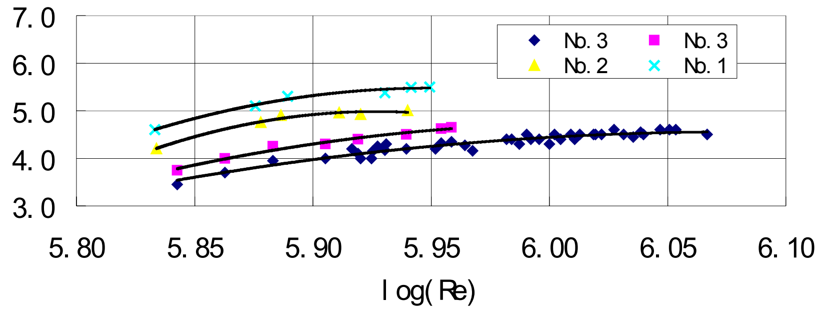

Figure 2 Relationship between the incipient cavitation number and the Reynolds Number for an Orifice Plate

orifice plate. Curves shown in Figure 2 indicate that the incipient cavitation number rises as the Re number increases and gradually approaches a horizontal line as an asymptotic line. Their tendency can be expressed by the following functions:

$$\sigma_i = a - b\exp(-c\,Re) \quad (1)$$

in which a depends on constants indicating the shape of the orifice plate, and $b > c > 0$. When $Re > 7 \times 10^5$, the variation of b, c is not significant, the average values are : $b = 175$, $c = 0.737 \times 10^{-5}$ .It is evident that when the Re is large enough, the second term of the right side of the above-mentioned formula will approach to zero, a is the incipient cavitation number in prototype. Therefore, the incipient cavitation number in prototype can be estimated when scale effect has been taken into consideration and the σ_{im} at N1, N2, and N3 are 5.85, 5.50 and 4.90 respectively.

From Figure 2, one can see that when $Re < 8 \times 10^5$, the influence due to scale effect is quite remarkable ; the less the Re, the greater the influence will be ; hence the measured incipient cavitation number under small Re in model should never be directly scaled and used to forecast the cavitation behavior to prototype without modification for scale effect. It is only the case, when $Re > 10^6$, the σ_i will approach a definite value. Leaving out the Re number, the relative air content in water α/α_s is also an important parameter causing scale effect. The model test if carried out in a vacuum chamber, the ambient atmospheric pressure would be reduced to keep the σ number identical thereby making the air content in water reduced, the tensile strength of water increased thus leading the σ_i decreased. Then the cavitation phenomena in prototype will fail to be reproduced. The $\sigma_i - Re$ curves given in Fig. 2 are obtained approximately under the condition of $\alpha/\alpha_s = 0.1$.

3. Prototype observation

With an aim at witnessing the cavitation inception by means of acoustic method, prototype observation was conducted on Xiaolangdi Hydro-project. Model 8103 hydro-phone and Model 3560 double channel dynamic signal analyzer system, manufactured by B&K Company were used to detect the cavitation noise in the flow of No.1 tunnel spillway with multiple orifice plate. The said system is composed of PULSE frequency spectrum analyzer aided by computer and tailor-made software. It is capable to monitor two-channel, time domain signal and the variation of Fourier's frequency spectrum, having the function of real-time double-frequency analysis. The maximum frequency is 102.4 kHz. The whole measuring system is composed of what shown in the block diagram Figure 3

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Figure 3 Block diagram of measurement system

3.1 Arrangement of measuring points

No.1 tunnel spillway is provided with 3 sets of orifice place at the chainage between 0 + 124.25 m – 0 + 255.04 m.. In order to measure the cavitation noise in water flow for each orifice plate distinguishing cavitation phenomena, measuring points are arranged at the location 1 D downstream of each orifice plate and installed with hydrophone. The serial numbers of measuring points from upstream to downstream are N1, N2 and N3 successively. The corresponding pressure taps are also provided at the left side wall on the center line of the same elevation, 0.5 D upstream of each orifice plate, bearing the serial numbers of P1, P2, and P3 successively. The locations and elevations of measuring points are listed in Table 1 and illustrated in detail as shown in Fig. 4.

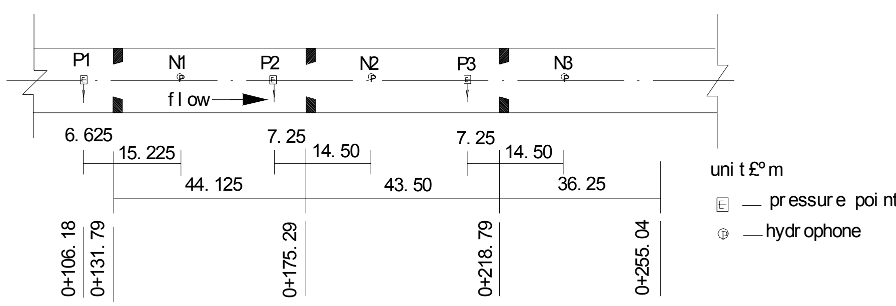


Figure 4 Arrangement of measuring points

Table1 Arrangement of measuring points for cavitation flow noise

Serial number	Chainage (m)	Elevation (m)	Serial number	Chainage (m)	Elevation (m)
N1	0 + 146.915	139.83	P1	0 + 124.54	139.20
N2	0 + 189.790	139.57	P2	0 + 168.04	138.95
N3	0 + 226.04	139.37	P3	0 + 211.54	138.70

3.2 Method of analysis and judgement of cavitation in water flow

During the process of bubble collapse in cavitation flow, cavitation noise with high frequency will produce.

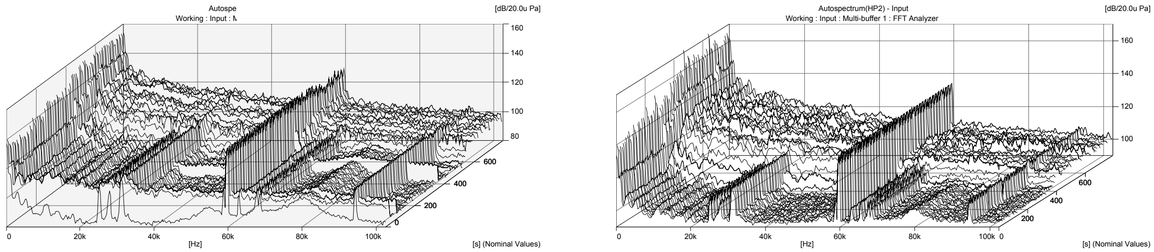
The SPL of cavitation noise will be evidently higher than what happened by the oscillation of conventional gas bubble in water flow. In the process of cavitation inception, development and collapse, the bubble will experience volume expansion, compression, until collapse and vanishing. The source of cavitation noise is of the source of volume oscillation, having the characteristics of singlet sound source. Such sound source radiation in liquid media attenuates quite slowly as the distance increases. Using specially designed underwater noise measuring facility to monitor the acoustic signal at a range of certain distance from the cavitation source, one can obtain the cavitation noise signal. Therefore, when people are conducting cavitation research on water flow, they are able to analyze and distinguish the cavitation inception behavior by means of acoustic approach. The noise of water flow varies as the magnitude of velocity and the turbulence level in prototype. Therefore it is unable to determine the background noise under the same condition of hydraulic parameters such as velocity, pressure in advance. However, the noise due to turbulence in water flow comes from the oscillation of gas nucleus, which has the rise tendency as the increase of velocity and turbulence level. Under the same condition of water quality, certain correlation is in existence between the background noise generated in water flow and hydraulic parameters of the flow field. In the process of gradual variation of velocity and pressure, the corresponding flow noise will also vary gradually, the variation of which should have certain regularity and continuity. The flow pattern at the vicinities of multi-orifice plates is somewhat similar to what happened in submerged shooting flow. The velocity and pressure can be adjusted through the control of operating gate. Under the condition of keeping the upstream water level practically unchanged, increasing the gate opening, it will make the pressure in tunnel spillway lowered, and the velocity of flow passing the orifice plate increased, thereby making cavitation number decreased. When the cavitation number of water flow is less than the incipient cavitation number of the orifice, cavitation occurs. The noise due to bubble collapse will be the main noise source, the SPL in the high frequency range sharply increases. The noise frequency spectrum curve will also be suddenly changed.

3.3 Prototype observation findings and analysis

3.3.1 Water flow noise in the process of continuous gate opening

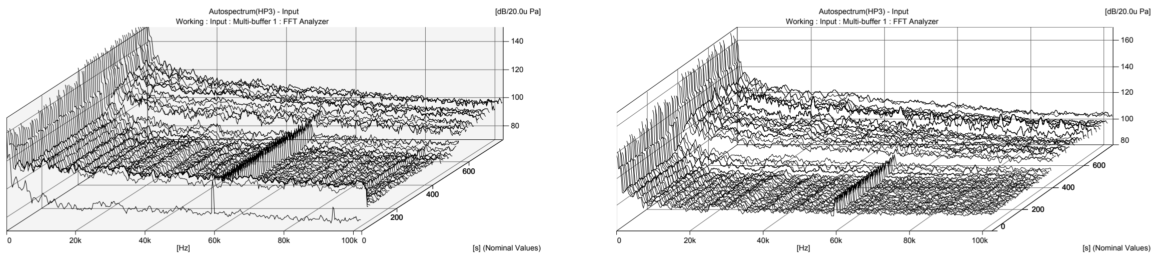
Repeated monitoring of water flow noise on N2 and N3 was conducted during the continuous gate opening. Based on the whole process of gate opening, the whole time of monitoring was set to be 12 minutes. There were 801 lines of frequency spectrum, each spectrum line taking 10 samples in average, the time interval being 10 seconds.

Figures 5 and 6 illustrate 3-D distribution of real time monitoring of water flow noise spectrum on measuring points N2 and N3, which evidently show the time variation of flow noise frequency spectrum curves during the process of gate opening. From these two figures, one can see that the frequency spectrum level has had a sudden rise pulse in the frequency band exceeding 10 kHz during the continuous gate opening.



(a) First run gate opening process **(b) Second run gate opening process**

Figure 5 Variation of flow noise frequency spectrum on N2 during continuous gate opening

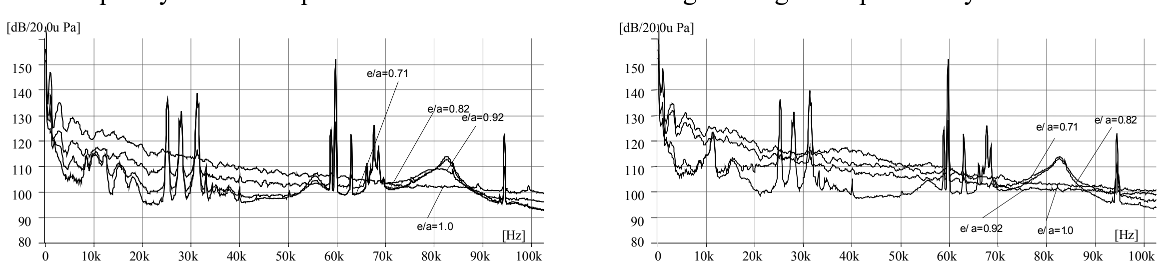


(a) First run gate opening process **(b) Second run gate opening process**

Figure 6 Variation of flow noise frequency spectrum on N3 during continuous gate opening

3.3.2 Water flow noise in the process of fixed gate opening

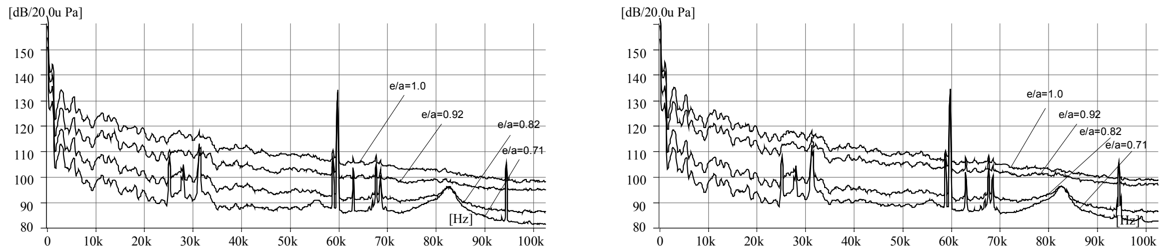
Two runs of observation on flow noise were conducted at relative gate opening e / a being 0.71, 0.82, 0.92, and 1.0 respectively. In the first observation period, the upstream level was in the range of 210.18 m – 210.28 m. In the second observation period, the upstream level was in the range of 210.23 m – 210.26 m. The curves of flow noise frequency spectrum, measured in two runs on N3 at various gate openings are shown in Figures 7, 8 and 9. Comparing the results obtained in these two runs, one can find that the variation of noise frequency spectrum curves has had the agreeable tendency. The SPL of flow noise at various frequency bands are quite close. The observation findings have good repeatability.



(a) First run observation **(b) Second run observation**

Pool level: 210.20 m – 210.26 m **Pool level : 210.20 m – 210.28 m**

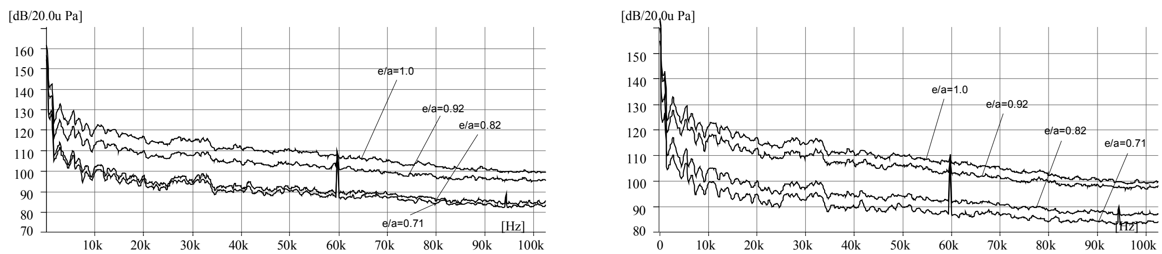
Figure 7 Flow noise frequency spectrum curves of N1 under different gate opening



(a) First run observation **(b) Second run observation**

Pool level : 210.20 m – 210.26 m **Pool level : 210.20 – 210.28 m**

Figure 8 Flow noise frequency spectrum curves of N2 under different gate opening



(a) First run observation **(b) Second run observation**

Pool level : 210.2 m – 210.26 m **Pool level : 210.20 m – 210.28 m**

Figure 9 Flow noise frequency spectrum curves of N3 under different gate opening

In the process of continuous gate opening, taking the cavitation number at the moment when the SPL of flow noise is suddenly rising, as the incipient cavitation number σ_i , the relative gate opening being 0.9 , the σ_{ip} at N1, N2, and N3 are equal to 5.85, 5.65 and 5.03 respectively. As compared to 1:40 model test[1], after having been modified due to size effect and velocity effect in terms of Re number effect, the σ_{im} at N1, N2, and N3 are 5.85, 5.50 and 4.90 respectively, which are quite agreeable with the findings obtained in prototype observation.

4. Conclusion

(1) .Acoustic approach is a promising method to detect cavitation inception. It is more objective and scientific, being capable to be free from personal subjunctive prejudice. Cavitation inception has been well witnessed by SPL both in model test and prototype observation.

(2). The prototype observation carried out at Xiaolangdi Hydro-project on the Yellow River has yielded satisfactory results. It has well verified the findings obtained in model test and confirmed the importance of scale effect problems.

(3). The scale effect in cavitation modeling has long been of serious concern. It remains a vital hard nut to be cracked, making great difficulties to scale the model test findings directly to prototype. From the comparison between the present prototype observation and the 1: 40 model test conducted in a large-sized vacuum chamber, taking Reynolds number as the main parameter to reasonably modify the incipient cavitation number of multi-orifice plates due to scale effect is necessary. After having modified the scale effect, it can well predict the cavitation behavior in prototype, as expected.

Reference

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